Chapter 7

Ocean Cage Culture

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It is widely acknowledged that future increases in seafood production will likely come from farming, not fishing. The growth of land-based and nearshore marine aquaculture in many developed countries is constrained by space, economics, and environmental concerns. Open ocean or offshore waters offer a tremendous potential for expansion of the marine farming sector, and developments to date indicate that it is indeed feasible to install, maintain, and operate cage culture systems in high-energy offshore waters. Despite evidence that open ocean farming is possible, production has been limited thus far and a number of technical, operational, economic and political challenges must be addressed before large-scale production in true open ocean conditions can be realized.

7.1 The context for open ocean farming

Population growth and consumer preference have resulted in a growing demand for seafood, a trend that is projected to continue into the future (FAO 2006). Production from capture fisheries has leveled off and by most projections will remain stagnant or decline depending on management and regulatory measures implemented by fishing nations (NOAA 2005a; Worm *et al.* 2006). In contrast, aquaculture production has increased by nearly 10% each year since 1980, and has played an important role in filling the gap between seafood supply and demand. There are signs, however, that the rate of growth may have peaked for

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land-based and nearshore marine culture due to political, environmental, economic, and resource constraints (FAO 2006). Expansion of land-based culture is limited primarily by economics, particularly in developed countries where costs associated with land, capital equipment, and energy required to pump and filter water are prohibitive. For nearshore marine cage culture, available space is the primary limiting factor. Suitable sites for marine faming in protected coastal waters are, for most countries, quite limited to begin with and those that do exist are used for a multitude of recreational and commercial activities with which aquaculture must compete for space. Expansion of large-scale finfish farming in coastal waters is also constrained by environmental concerns, engendered primarily by the unintentional and undesirable environmental effects of salmon farming that occurred during a period of rapid industry growth in the 1980s and 1990s. Incidents of seafloor pollution from uneaten feed and fish wastes (Hargrave *et al.* 1993), outbreaks of deadly diseases (Hovland *et al.* 1994), interaction with marine mammals and other predators (Nash *et al.* 2000), overuse of antibiotics and biocides, and escapement of fish from sea cages were documented. While the worst conditions were associated with inappropriate sites or poorly managed farms (NOAA 2001), the growing opposition to cage culture was nonselective and all salmon farming—and by way of extension, cage culture for many species—has been deemed environmentally "unsustainable" by opponents of marine fish farming.

Responding to criticism from environmental groups and pressure from regulatory agencies, the industry began to improve management practices to address environmental concerns. Better feed formulations and careful monitoring of the feeding response of fish resulted in improved feed conversion ratios and less waste (DFO 2005). Vaccines drastically reduced the use of antibiotics (Knapp *et al.* 2007). More informed site selection led to a reduction in benthic impacts and fallowing allowed impacted sites to recover. Voluntary codes of conduct that embraced environmental protection were developed in the United States, Canada, Europe, and Australia. While environmental performance has greatly improved, public perception of coastal fish farming has not, and opposition persists—if anything, it has increased in recent years. In the current climate, new permits to farm salmon or other species in coastal waters are difficult, if not impossible, to obtain.

In developed countries, conflict with coastal residents and tourist-related businesses over aesthetic values, primarily over water views from shorefront property, have also affected the permitting of new cage culture sites. As the demographic of coastal communities continues to change and new residents place more value on views and recreation than food production, these conflicts will only increase. Given the constraints on expansion of current methods of production, it is clear that alternative approaches are needed in order for the marine aquaculture sector to make a meaningful contribution to the world's seafood supply.

Farming in open ocean marine waters (as used in this chapter, synonymous with "offshore farming") has been identified as one potential option for increasing production and has been a focus of international attention for more than a decade. Despite this global interest, industry development in open ocean

waters has been measured, primarily due to the significant technical and operational challenges posed by wind and wave conditions in most of the world's oceans (Ryan 2004). Open ocean farming requires a completely new engineering approach since equipment and methods currently used for fish production in protected nearshore waters are largely unsuitable for the open ocean. In addition, the scale of investment required to develop and demonstrate new technologies and methods for offshore farming is yet to be determined, though most engaged in this endeavor would agree that it will likely be substantial.

Despite these challenges, there is sufficient rationale for pursuing the development of open ocean cage culture. Favorable features include ample space for expansion, tremendous carrying capacity, reduced conflict with many user groups, lower exposure to human sources of pollution, the potential to reduce some of the negative environmental impacts of coastal fish farming (Ryan 2004; Helsley & Kim 2005; Ward *et al.* 2006; Langan 2007) and optimal environmental conditions for a wide variety of marine species (Ostrowski & Helsley 2003; Ryan 2004; Benetti *et al.* 2006; Howell *et al.* 2006). For many countries where cost, environmental concerns, limited space and competing uses have restricted growth of land-based and nearshore marine farming, few other options for significant expansion exist.

7.2 Characterization and selection of open ocean sites

7.2.1 Definition

Before discussing approaches to open ocean aquaculture development, it is important to establish a clear definition of the term. For most engaged in this sector, the terms *open ocean* and *offshore* are interchangeable and are generally accepted to mean farming in locations that are subjected to ocean waves and currents and are removed from any significant influence of land masses, rather than a set distance from shore. Clearly, a wide range of sea conditions falls under this broad definition. Ryan (2004) reported on a site classification system for marine waters developed in Norway that is based on significant wave height exposure (table 7.1). While this classification method is instructive, knowledge

Table 7.1 Norwegian classification of offshore waters based on significant wave heights (Ryan 2004).

Site Class	Significant Wave Height (Meters)	Degree of Exposure
1	<0.5	Small
2	0.5–1.0	Moderate
3	1.0–2.0	Medium
4	2.0–3.0	High
5	>3.0	Extreme

of the full range of conditions that occur at a particular site is needed to design and sufficiently test robust engineered systems and to develop safe and efficient operating procedures.

7.2.2 Site selection criteria and methods

The suitability of sites for open ocean farming is dependent on a number of criteria, many of which are also considerations for nearshore sites. These include proximity to infrastructure such as ports, processing, and distribution centers; physical and biological criteria such as bathymetry, seabed characteristics and contour, current velocities, temperature profiles, dissolved oxygen, turbidity, and the frequency of occurrence of harmful algal blooms. The most important additional feature of offshore sites is wave climate. Significant wave heights, wave periods, the frequency and duration of high energy storm conditions and combined forcing of waves and currents must be known in order to determine whether a site is suitable, and if so, what type of technology is required for farming. For example, some sites may be relatively calm most of the time and infrequently experience occurrences of severe weather such as tropical cyclones. Other sites may never have waves greater than three meters but they may experience short period waves in this range most of the time—conditions that would cause excessive wear and tear on equipment and make surface operations such as feeding and harvesting difficult. For the former scenario, technology operated at the surface with the option to submerge for short periods would be appropriate, while for the latter it is likely that submersible cages supported by automated technologies would be needed.

It is imperative that a thorough evaluation that includes the parameters described above be conducted before proceeding with development of a site for farming. The requirements for data and subsequent analysis can be substantial; however, the use of advanced oceanographic technologies can greatly facilitate this task. Multibeam sonar and three-dimensional visualization can generate a wealth of data on seafloor contours and texture to inform mooring system design and placement. Collection of time-intensive data on temperature, salinity, dissolved oxygen, turbidity, and fluorescence can be greatly facilitated by strategic deployment of in-situ instrumentation at appropriate depth intervals in the water column. Additional instrumentation should include Acoustic Doppler Current Profiler (ADCP) current meters that can profile current velocity and direction throughout the water column, wave sensors that can give precise data on wave height, steepness, direction and period, and meteorological sensors to measure air temperature and wind speed and direction. Many countries have buoy arrays in coastal and shelf waters that can provide long-term data on regional climatology to aid site evaluation; however, collection of site-specific data is critical. Assessment of the potential for the effects of global climate change on critical site features such as water temperature and storm frequency and intensity should also be considered.

The data collection period required for site evaluation will vary, depending on local and regional environmental and meteorological conditions. Good baselines for some parameters can be established in a relatively short time frame (one year), others such as the frequency, duration, and severity of storms or blooms of toxic algae are less predictable and it may take longer to determine the suitability of a particular site.

In addition to physical, chemical, and biological characteristics of a site, other human uses in the area such as shipping, fishing, and mining must be identified in order to avoid conflicts. Other factors including use of the area by marine mammals, the likelihood of encounters with large predators, the location of important spawning grounds for indigenous fish, and proximity of sensitive biological communities must also be considered. Many countries require characterization of the benthic community and sediment quality to establish of preoperational baselines of environmental quality.

7.3 Technologies for open ocean farming

Initial attempts at offshore farming relied to a large extent on trial and error. Cages and mooring systems used in sheltered sites were simply moved to ever more exposed locations, and, as might be expected, many failures occurred. In addition to catastrophic failures, excessive wear and tear on cages, nets, and mooring components meant that crews had to spend more time on maintenance, adding to the production cost for the farm owner. It became clear that new technologies were needed to farm in open ocean waters.

7.3.1 Engineering design and assessment

Beginning in the early 1990s, several groups began to apply a more sophisticated engineering approach to cage (Loverich & Goudey 1996; Lisac 1996) and mooring design (Fredricksson *et al.* 2004), assessment of the structural integrity of cage materials (DeCew *et al.* 2005), and modeling the effects of hydrodynamic forcing on cages and netting (Lader & Fredheim 2003; Swift *et al.* 2006). An approach that includes numerical modeling (e.g., finite element modeling), scale model testing and in-field measurement of line tensions and physical forcing on cage and mooring components, has been shown to effectively inform the design, materials selection, and integrity of offshore systems and to reduce the possibility of system failure (Fredricksson *et al.* 2003).

7.3.2 Mooring and cage systems

Mooring systems for ocean cages include modifications of multi-cage grid systems commonly used for nearshore cages (fig. 7.1), single point moorings for individual cages (fig. 7.2), or cage arrays (fig. 7.3) and novel constructs such

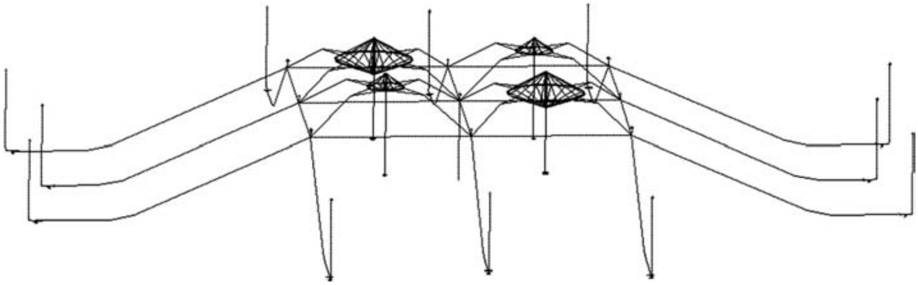

Figure 7.1 A schematic of the submerged grid mooring system designed by the University of New Hampshire, United States. This system can accommodate up to four submersible cages.

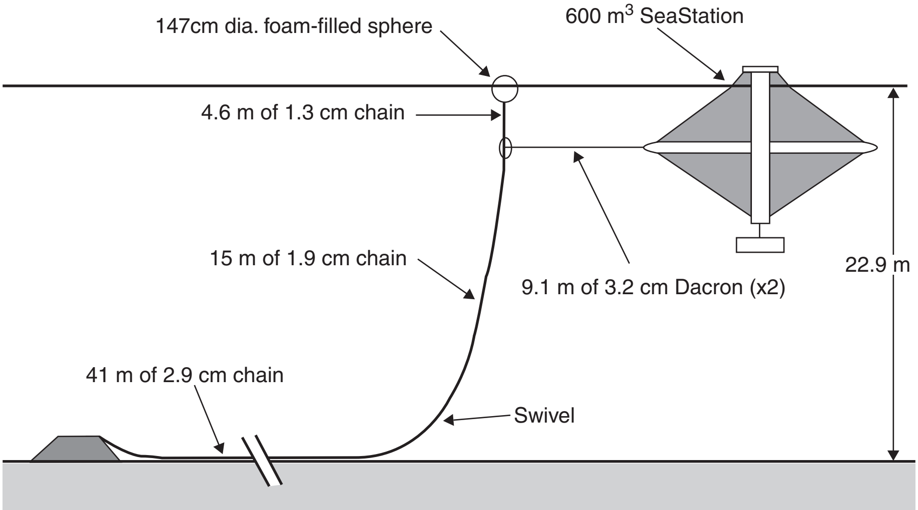

Figure 7.2 A schematic of the single-point mooring system designed by MIT to anchor an individual SeaStation cage.

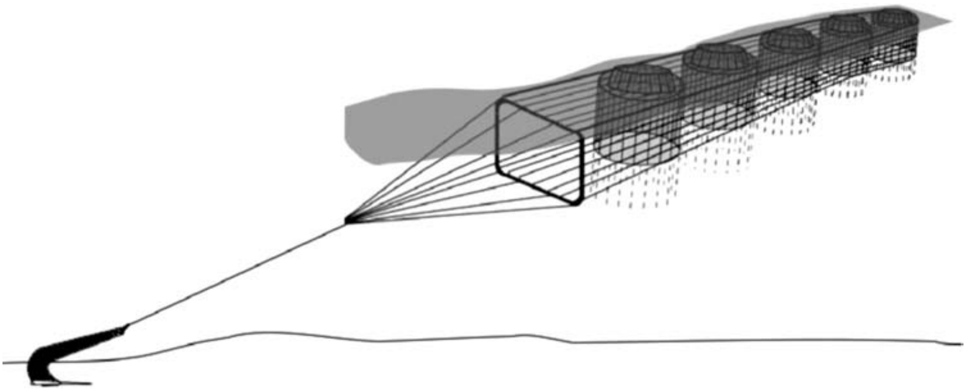

Figure 7.3 The single point mooring system designed by the Israeli company SUBflex to anchor an in-line array of submersible cages.

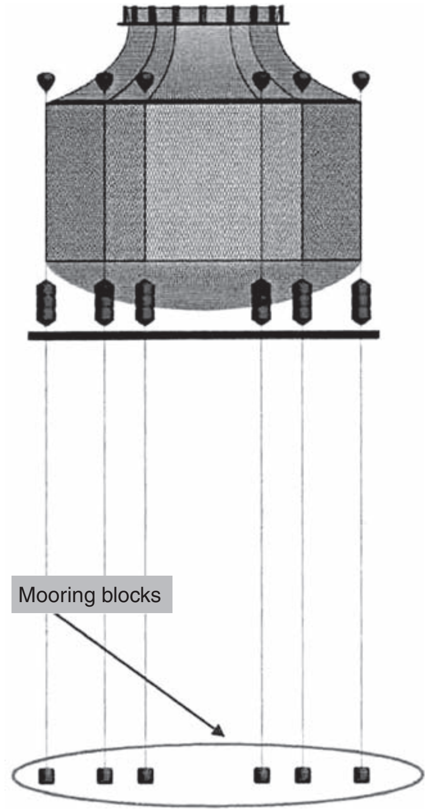

Figure 7.4 The tension leg mooring and semi-submersible cage system developed RefaMed, Italy.

as tension leg moorings (fig. 7.4). Mooring components typically include dead-weight anchors or embedment or plow-type anchors, heavy-chain ground tackle, synthetic braided or twisted rope, and specialized rings and plates to connect mooring component lines. Submerged grid systems also utilize buoyancy at critical junctions to provide tension and rigidity for the mooring system (fig. 7.5).

A wide array of cage technologies has been applied or proposed for use in open ocean sites. These technologies have been described in detail by Scott and Muir (2000), and more recently by Ryan (2004), though a number of new technologies have emerged in the concept or prototype phase since those documents were published. The previously mentioned authors parsed cage technologies into several categories based on structural and operational properties; however, for the purpose of simplicity, most cages can be divided into one of two main categories: (1) surface referenced or gravity cages that use steel, high density polyethylene (HDPE), or rubber collars to float the cage and net; and (2) submersible cages. Further subdivision can be made based on how they are moored to the seafloor and whether they are of flexible or rigid design and construction. In addition, some amount of hybridization has blurred the distinction between

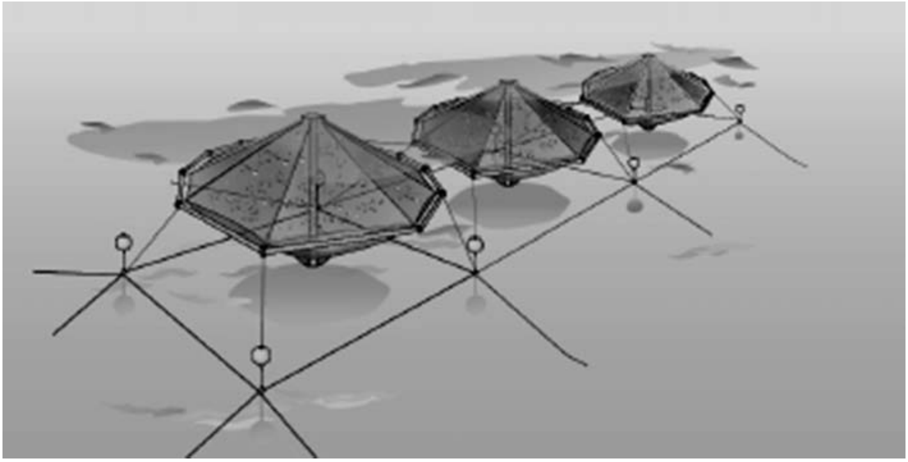

Figure 7.5 A linear grid mooring system developed by the US company Ocean Spar to anchor multiple SeaStation cages. The buoyancy attached to the grid corners provides the tension to maintain the desired grid geometry.

the two categories and some older technologies and recent innovations defy categorization.

Given the wide range of sea conditions that fall under the definition of open ocean aquaculture, no single cage technology can be considered ideal or even appropriate for use under all circumstances. Currently, the greatest production in exposed locations is achieved with gravity cages. Large rubber (e.g., Bridgestone, Dunlop) and HDPE (e.g., PolarCirkel, Fusion, AquaLine) collar cages (fig. 7.6)

Figure 7.6 A photo of a large diameter HDPE collar gravity cage used for tuna penning at a semi-exposed site in the Mediterranean Sea.

are in use for salmon production in high-energy sites in Ireland, Scotland, the Faeroe Islands, and New Brunswick, Canada. Similar technologies are used in the Canary Islands and the Mediterranean Sea for bass and bream culture. Tuna fattening operations in Australia, the Mediterranean, and Mexico also use large HDPE collar cages in exposed and semi-exposed sites. The trend in recent years has been toward increasingly larger diameter (e.g., 50 meters) HDPE collar cages. The increased size results in greater flexibility in response to waves, as well as enormous production volumes that now exceed 60,000 cubic meters.

There are a number of advantages to the use of HDPE collar gravity cages: a relatively long history of use and operational familiarity at sheltered sites; their ability in some circumstances to use existing automated infrastructure such as air-piped centralized feeding systems; and their low cost relative to containment volume. However, there are also limitations to their use (Fredricksson *et al.* 2007). These include structural failures, operational difficulties related to feeding, harvesting, fish monitoring in rough weather, and increased maintenance to repair and replace system components due to excessive wear and tear. All of these limitations can affect production schedules and increase operational costs. Surface conditions such as waves and high currents during storms can also compress cage volume and can have detrimental effects on the fish.

Manufacturers of rubber and HDPE collar gravity cages continue to make structural improvements and several companies have developed submersible versions of their cages. These adaptations are likely to result in more robust systems and the option to submerge during storms will expand the range of sites in which these systems can be operated. It is likely that in the near term, these technologies will continue to be used for open-ocean farming at suitable sites.

Variations on the gravity cage include the Farmocean (fig. 7.7), which uses a rigid steel umbrella-like frame for floatation. The SADCO-SHELF (fig. 7.8) uses a similar steel superstructure and can also be operated in a submerged position. Both cages incorporate automated feeders in the structural framework. Due in part to high cost per volume as well as some structural and operational issues, neither of these cages has achieved wide-scale adoption.

Fully submersible cages include the semi-rigid SeaStation from Ocean Spar and the relatively new, rigid construction AquaPod from Ocean Farm Technologies (fig. 7.9). Moored individually or in a submerged grid system (fig. 7.5), SeaStations have been used successfully for nearly a decade in very rough conditions, including a site off the coast of New Hampshire in the northwest Atlantic, where significant wave heights can exceed nine meters (Chambers *et al.* 2007). There are currently more than fifty SeaStations deployed in sixteen countries for growout of a wide variety of species.

Despite their demonstrated ability to withstand extreme sea conditions and provide a stable environment for fish, fully submersible cages have not achieved widespread use for a number of reasons: The cages are small by commercial salmon farming standards (3,000 to 6,000 cubic meters), are relatively expensive, and are considered by some in the industry to be difficult to feed, harvest, and clean. Many routine operations require scuba diving, which is time consuming, expensive, and dangerous. Recent improvements to both the SeaStation

Figure 7.7 A photo of the modified gravity cage system developed by Farmocean International of Sweden. The top center component of the structure is the built-in feeding system.

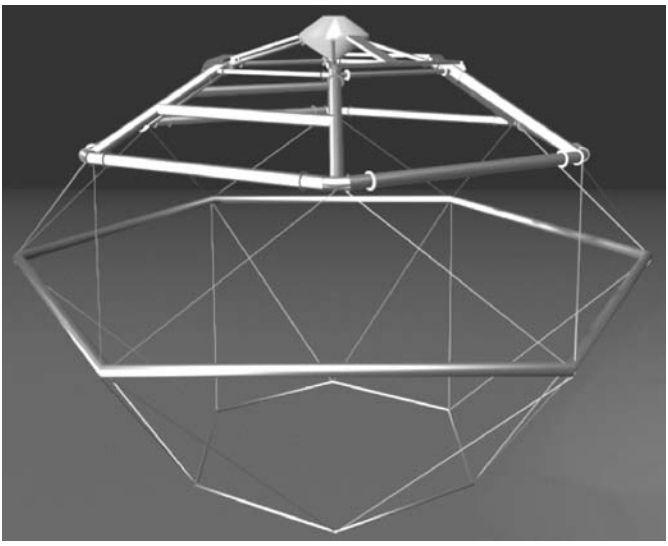

Figure 7.8 A drawing of the framework of the submersible cage system developed by SADCO-SHELF of Russia.

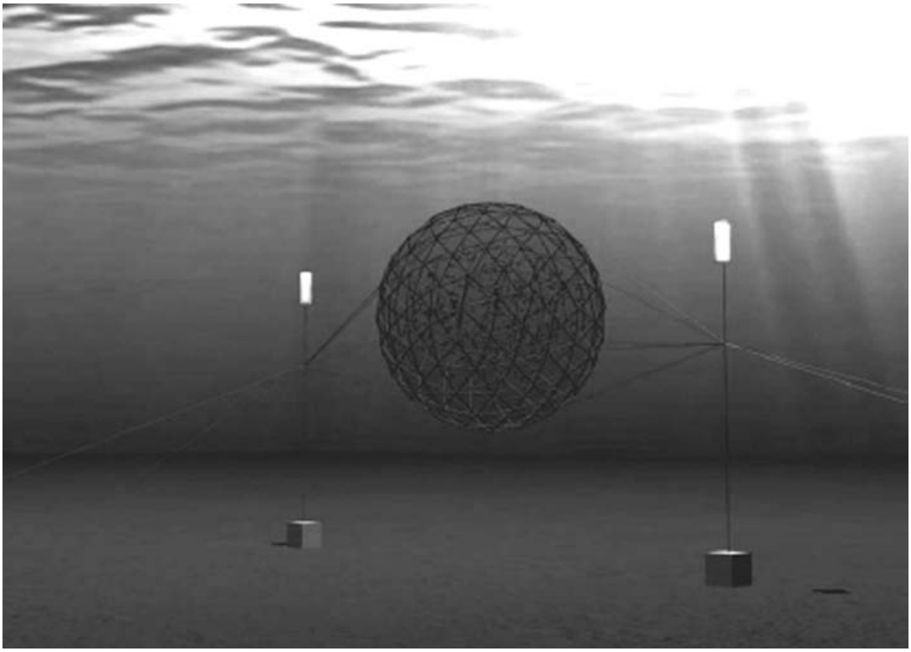

Figure 7.9 An artist's rendition of the submersible AquaPod cage from Ocean Farm Technologies (United States) anchored in a two-point mooring.

and AquaPod cages have made some operations such as net cleaning, removal of mortalities, and harvesting safer and easier, and the companies continue to address the operational aspects of their cages. Both companies have developed larger versions of their cages, though even the largest of these designs is substantially smaller than gravity cages now in use. Farms that are currently using fully submersible systems tend to be small (two to eight cages) with relatively low production volumes of high-value niche species.

A number of new designs for submersible cages have emerged in recent years, such as the 40,000 cubic meter Ocean Globe from Byks of Norway, but few of them have been built at full scale and virtually none have been tested in field situations. Innovation in submersible cage technology continues and several new designs are due for unveiling in the near future; however, reluctance by the industry to embrace submerged technologies has hampered their development.

There are several cage technologies—some implemented and others in the design phase—that do not fall neatly into either the gravity cage or submersible categories. Ocean Spar developed a 20,000-cubic-meter anchor tension cage in the 1990s called the AquaSpar that uses spar buoys rather than a floatation collar to provide buoyancy and create the cage volume. RefaMed in Italy has developed the tension-leg mooring mentioned previously to secure what is essentially an inverted gravity cage (Lisac 1996). A number of these cages are in use

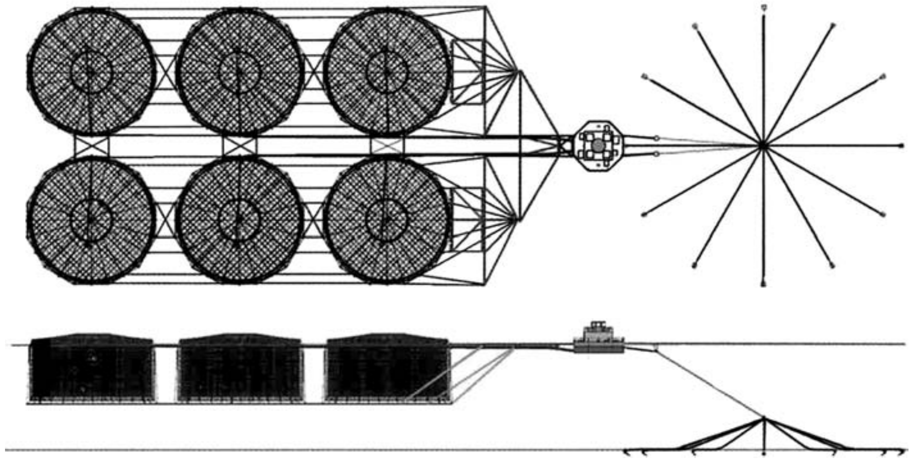

Figure 7.10 Drawings of top and side views of a mooring and cage system developed by Aquaculture Engineering Group from New Brunswick, Canada.

in the Mediterranean for bass and bream culture. The New Brunswick, Canada, company Aquaculture Engineering Group (AEG) has developed a unique farming concept that integrates an array of modified gravity cages with an automated feeding system and current velocity deflector designed for use in the high-current open waters of the Bay of Fundy (fig. 7.10). The entire system is anchored to the seafloor by a single-point mooring and orients itself in the direction of the current (fig. 7.10). The Israeli company SUBflex has developed a similar design that utilizes a single-point mooring and an in-line array of cages, though the SUBflex system is fully submersible (fig. 7.3). A concept for an untethered, ocean drifter cage was developed by Ocean Spar and the Massachusetts Institute of Technology in the 1990s (Goudey 1999), but it has not advanced beyond the concept and design phase for more than a decade.

7.3.3 Supporting technologies

In addition to the challenge of developing sufficiently robust containment and mooring systems, offshore farming presents challenges for nearly all aspects of day-to-day farm operation. Methods and equipment developed for routine operations such as feeding, harvesting, and monitoring at sheltered sites have been designed for calm sea conditions, and, for the most part, cannot be directly transferred to the open ocean environment. Development of alternative operational systems has not kept pace with ocean cage development and farmers have struggled to integrate existing, as well as new and unproven, supporting technologies into offshore installations.

Of all operations, feeding is probably the most important. Inshore approaches, which include dispensing feed by cannons from a service vessel or automated

Figure 7.11 A photo of the multi-cage automated feeding system developed by the University of New Hampshire and Ocean Spar at the university's experimental open-ocean farm.

feeding with blowers mounted on centralized feed barges, are severely hampered by rough seas. An ideal feeding system for offshore aquaculture would be robust, remotely controlled, fully automated, able to accommodate the volume of food needed for a two- to three-week period and have a hydraulic rather than pneumatic feed delivery system. It would also ideally be capable of wireless transmission of in-cage video, environmental monitoring data or other information critical to farm operation. Though no system as described currently exists, some progress has been made. The Scottish company Gael Force has developed the Sea Cap, a concrete feed barge that has operated successfully in semi-exposed locations for several years. The University of New Hampshire (UNH) has developed two small (single cage), remotely operated feeders that have been in use since 2001 (Rice *et al.* 2003) and designed and built a larger multi-cage feeder in 2007 (fig. 7.11). Developed in conjunction with Ocean Spar, the feeder has four separate feed silos and can dispense feed hydraulically to four submerged cages (Turmelle *et al.* 2006). It also incorporates a two-way remotely operated communications system that operates in-cage video cameras to monitor fish behavior and response to feed introduction. The system also houses a unique acoustic tracking system that can continuously monitor behavioral and physiological responses of tagged fish to changes in environmental conditions (Howell *et al.* 2006). Farmocean and SADCO also have integrated automated feeding systems into their cage designs, and the Canadian company Aquaculture Engineering Group has developed an automated hydraulic feeder that is integral to their single-point mooring cage array.

Other routine offshore operations such as grading, harvesting, biofouling control, and removal of mortalities are complicated by sea conditions and additional strategies must be developed to make these practices safer and more efficient.

7.4 Finfish species cultivated in open ocean cages

Fish cultivated in open ocean cages include warm and cool temperate as well as tropical and subtropical species, though at present, cool temperate species predominate. In terms of production volume, the leading species is Atlantic salmon (*Salmo salar*), which are produced in gravity cages in Ireland, Scotland, Canada, Norway, and the Faeroe Islands. Sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus auratus*) are grown in gravity, tension leg, and submersible cages throughout the Mediterranean (Ryan 2004). Fattening of Northern Bluefin tuna (*Thunnus thynnus*) in large high-density polyethylene (HDPE) collar gravity cages takes place in exposed locations throughout the Mediterranean and has expanded dramatically in recent years. Other tuna fattening operations that use HDPE cages in exposed locations include Southern Bluefin tuna (*Thunnus maccoyii*) in South Australia, Pacific Bluefin (*Thunnus thynnus orientalis*), yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) in Mexico. In the northeastern United States, the University of New Hampshire operates an experimental open-ocean farm and has produced small quantities of Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinis*), and Atlantic halibut (*Hippoglossus hippoglossus*) in submerged SeaStation cages (Howell *et al*. 2006).

Warm temperate and tropical species produced in ocean cages include milkfish (*Chanos chanos*) in the Philippines; Florida pompano (*Trachinotus carolinus*) in Belize; summer flounder (*Paralichthys dentatus*) in Mexico; parrotfish (*Oplegnathus faciatus*) and olive flounder (*Paralichthys olivaceus)* in Korea; and golden pompano (*Trachinotus blochii*) in China. In Hawaii, Pacific Threadfin (*Polydactylus sexfilis)* and amberjack (*Seriola rivoliana*) are being grown commercially in submerged cages at open-ocean sites off Oahu and the Island of Hawaii. Another warm-water species of interest for open-ocean farming is cobia (*Rachycentron canadum*), which is currently produced in Puerto Rico and the Bahamas.

A number of additional marine species have been identified as having potential for open ocean production. In the United States, Sablefish (*Anoplopoma fimbria*) is a leading candidate for ocean farming in the Pacific northwest and California yellowtail (*Seriola dorsalis lalandi*), striped bass (*Morone saxatilis*), California halibut (*Paralichthys californicus*), and tuna (*Thunnus* sp.) have been proposed for open ocean culture in Southern California. Red drum (*Sciaenops ocellatus*), Florida pompano (*Trachinotus carolinus*), and tunas are being considered for the Gulf of Mexico in the United States. Mulloway (*Argyrosomus hololepidotus*) and yellowtail kingfish (*Seriola lalandi*) are under consideration for open ocean culture in Western Australia.

It is likely that many more species will come into production as offshore farming technologies are further developed; however, it should be noted that aside from a few species such as Atlantic salmon, sea bass, and sea bream (which are produced from established broodstock lines) many of the marine species under cultivation are the offspring of wild fish. Additional broodstock and hatchery work is needed to achieve desirable traits such as better and more uniform growth rates, improved food conversion ratios, delayed maturation, and disease resistance.

7.5 Environmental considerations

Like all forms of food production, the culture of marine species, whether practiced in land-based, nearshore, or offshore locations will have some effect on the environment. The effects can be both negative and positive and can vary depending upon the species, location, and farming practices. Concerns over the potential impacts of open ocean finfish farming essentially mirror those of nearshore cage culture (table 7.2; however, the degree of impact will likely be different, as will society's perceptions).

7.5.1 Cage effluents

Due to the limited number and relatively small size of the farms operating in open ocean sites, scientific knowledge of possible effects on offshore environments is not, as yet, well known. Data gathered to date would indicate that water column impacts from inorganic nutrients are unlikely (Helsley & Kim 2005; Langan 2007) although effects will vary depending upon production volume and the trophic status of receiving waters. Also, inputs from individual farms must be examined in the context of inputs from other sources in the region, including other farms. Benthic impacts from deposition of organic materials from waste feed and feces may also be reduced due to greater dispersion by ocean currents. Ryan (2004) cited a 2001 *Review of Benthic Conditions at Irish Fish Farms* conducted by Aquafact International Services Ltd., which reported benthic impacts were greatly reduced, if not more or less absent, beneath farms at exposed sites. At an experimental US offshore farm off the New Hampshire coast, no significant differences have been observed in sediment organic content or benthic community diversity between projected impact and reference sites after seven years of multi-species farming (Ward *et al.* 2006; Langan 2007). Alston *et al.* (2005) reported only minor changes to the benthos directly beneath cobia cages at an offshore farm in Puerto Rico, and Rapp (2006) found no changes in the organic content of the sediments beneath the cages at the same farm. Due to the small size of the farms in these studies, the results should not be viewed as convincing evidence that the potential for benthic impacts from offshore farms can be dismissed. A case in point is a benthic study conducted at an offshore

Table 7.2 Potential environmental impacts form marine net pen farming (NOAA 2005b).

Effects	Sources
Increased organic loading	• Particulate organic loading Fish fecal material Uneaten fish feed Debris from biofouling organisms Decomposed fish mortalities on the farm • Soluble organic loading Dissolved components of uneaten feed Harvest wastes (blood)
Increased inorganic loading	• Nitrogen and phosphorus from fish excretory products • Trace elements and micronutrients (e.g., vitamins) in fish fecal matter and uneaten feed
Residual heavy metals	• Zinc compounds in fish fecal material • Zinc compounds in uneaten feed • Copper compounds in antifouling treatments
The transmission of disease organisms	• Indigenous parasites and pathogens • Exotic parasites and pathogens
Residual therapeutants	• Treatment by inoculation • Treatment in feed • Treatment in baths
Biological interaction of escapes with wild populations	• Unplanned release of farmed fish • Unplanned release of gametes and fertile eggs • Cross infection of parasites and pathogens • Planned release of cultured fish for enhancement or ranching
Physical interaction with marine wildlife	• Entanglement with lost nets and other jetsam • Entanglement with nets in place, structures, and moorings, etc. • Attraction of wildlife species (fish, birds, marine mammals, reptiles) • Predator control
Physical impact on marine habitat	• Buoyant fish containment structures and mooring lines • Anchors and moorings
Using wild juveniles for growout	• Harvest of target and nontarget species as larvae, juveniles, and subadults
Harvesting industrial fisheries for fish feed	• Increased fishing pressure on the shoaling small pelagic fish populations

farm in Hawaii. Lee *et al.* (2006) reported an increase in opportunistic polychaete species and some loss of diversity in the benthic community, though these changes were spatially limited to areas immediately beneath the cages. As this study demonstrates, benthic impacts may be reduced in offshore environments; however, an expectation of "no impact" is unrealistic.

The degree of environmental change that will be tolerated must be decided by governing bodies in their respective jurisdictions, although it would be advantageous to establish international agreement on environmental performance standards with the caveat that some flexibility in the measured parameters is needed to account for site differences. There is no need to create standards from scratch. Based on existing knowledge of benthic impacts from nearshore farms, standards that have been developed for ecosystem protection in countries including Australia, Ireland, Norway, Scotland, and the United States have many common features and provide a good starting point for addressing environmental concerns.

Models, particularly those that integrate hydrodynamic, physical, and biological processes, can play a major role in predicting potential impacts of offshore farming. They enable scenarios to be run to forecast possible effects at specific farm sites as well as broader ecosystem effects. Farm-focused models such as AquaModel (Rensel *et al.* 2006) and DEPOMOD (Cromey *et al.* 2002) that use site-specific hydrodynamic, sediment, and biological data to simulate water column and benthic effects can be used to evaluate different management and production strategies. Site-specific models are also useful for identifying depositional areas and locating monitoring stations. Cumulative effects must also be considered as the offshore sector scales up so ecosystem models will be needed for broad area management.

It is reasonable to assume that monitoring will be required to ensure environmental compliance and to satisfy stakeholders that individual farms and the collective industry are operating in an environmentally responsible manner. Monitoring methods to determine the degree of organic enrichment vary in cost, clarity of interpretation, and the ability to standardize methods and establish meaningful performance standards. Detailed enumeration of benthic species obtained from sediment grab samples may be required during the initial site assessment to establish baselines and during the first few stocking cycles; however, this type of monitoring is very expensive and time consuming. Ideally, video or photographic analyses coupled with some type of chemical measurement such as Total Organic Carbon (TOC) or Loss on Ignition (LOI) that have been calibrated against this information would replace benthic monitoring and reduce costs for farm owners.

7.5.2 Diseases and parasites

Open ocean culture may offer some fish health benefits, which in turn may reduce the risk of transmission of parasites and diseases to wild populations as well as

reduce the need for treatments and therapeutics. Ryan (2004) reported lower incidence of sea lice at open ocean salmon farms in Ireland, which he attributed to dispersion of the planktonic stage of the ecto-parasites. One species of sea lice, *Lepeophtheirus salmonis*, is known to aggregate at the mouths of estuaries; therefore, placing salmon farms further offshore would greatly reduce exposure to this parasite (Costello *et al.* 2004). In addition, lower stress levels and better fish health observed at offshore farms have been attributed to the more stable temperature and salinity regimes, as well as the higher oxygen concentration and reduced ammonium levels that result from the greater water exchange through cages (Ryan 2004; Benetti *et al.* 2006; Howell *et al.* 2006). Bricknell (2006) concluded, "Offshore aquaculture offers many opportunities to reduce disease interactions between wild and farmed fish."

7.5.3 Escapement

The high-energy conditions of offshore sites increase the risk of fish escapement due to catastrophic equipment failure; therefore, the robustness of engineered systems (e.g., cages and moorings) must be carefully matched to site conditions. Some fish species under development for offshore farming are particularly prone to escapement. Cod, for example, will bite holes in netting material and escape from cages (Moe *et al.* 2007), so more durable alternatives to woven netting are needed. Also, since visual inspections of equipment by divers are more difficult and dangerous at offshore sites, automated systems such as video surveillance or acoustic abundance estimators may be required to monitor escapement. The major concern over salmon escapement from nearshore net pens is biological interactions with wild salmon. Moving farms offshore and away from salmon spawning rivers would greatly reduce this risk.

7.5.4 Marine mammal and predator interactions

Farming offshore may reduce exposure to coastal predators such as pinnipeds; however, exposure to other large predators such as sharks may increase. This risk can be managed through careful site selection to avoid known aggregation areas of local predators, prompt removal of dead or moribund fish, and the use of more robust containment barriers. The chance of encounters with protected species (e.g., whales, sea turtles) may also increase; however, entanglement with the mooring lines typically used for ocean cages is unlikely. Endangered whales are frequently sighted in close proximity to an open-ocean farm off the coast of New Hampshire and no adverse interactions have occurred in nine years of farming at this site (Ward *et al.* 2006).

7.5.5 Seed and feed issues

Issues such as the use of wild juveniles, which has been standard operating procedure for tuna penning and the use of industrial fish as feed ingredients, are essentially the same for offshore as for nearshore farming. There have been some advances in hatchery production of juvenile tuna species; however, it may be years before large quantities of hatchery produced juveniles are available for ongrowing. Significant progress has been made in developing alternatives to fish meal and fish oil, and continued research and development is likely to produce economically and nutritionally viable substitutes.

7.6 Future prospects and challenges

Developments over the past two decades indicate that fish farming open ocean environments is feasible and that there is potential for large-scale production of a wide variety of species. Conflicts with other uses can be significantly reduced, though they are not totally eliminated. Potential conflicts with capture fishing, navigation, and offshore energy production must be considered when selecting sites for offshore farming. There is also some evidence to support the premise that environmental impacts can be reduced by farming in offshore environments. Additional information on the potential effects of large-scale production is needed is needed to inform the development of rational policies and counter the negative perceptions of marine farming. Ideally, development of offshore farming should take place within the context of overall ocean management in order assure compatibility with other uses and consistency with broader goals to restore and sustain the health, productivity, and biological diversity of the oceans.

Significant progress has been made in the development of new marine species and engineered systems for offshore farming; however, a number of technical challenges remain. Hatchery technology has been developed for a number of marine fish species, though additional time and investment is needed to establish broodstock lines and the infrastructure to produce and transport large quantities of robust fingerlings. Open ocean farms may need to be coupled with nearshore farms to provide appropriate sites for intermediate stages of stocks, as larger juveniles may be needed for offshore cages. Nearshore farms can also be used as holding facilities for market-ready stock when weather conditions prohibit safe harvesting at offshore sites. There are a number of proven cage and mooring systems available, although they need to scale up in order to achieve the production volumes required for economic viability. Further development of supporting technologies is needed, including ocean-going service vessels, automated feeders, and remote-control observation and communication systems. Therefore, substantial and sustained investment in research and development from public and private sectors must be secured. In particular, research should focus on the development of highly mechanized and fully integrated offshore

farming systems, to achieve greater efficiency and ensure worker safety in the conduct of routine operations. Until “turnkey” systems that are essentially autonomous are available and economic viability of offshore farming can be demonstrated, expansion of this sector in the near future will be limited. A logical next step to hasten the development of offshore farming would be to establish commercial-scale offshore demonstration farms supported by a combination of public and private funds where technologies can be tested at reduced financial risk for the private sector and a greater understanding of the environmental effects of offshore farming can be gained to inform a rational regulatory framework. Demonstration farms would also be useful for training vessel operators and farm personnel to work safely and efficiently in offshore environments.

Though the complexity and scale of the challenge for offshore aquaculture development is formidable, the potential economic and health benefits of a sustainable ocean farming industry are enormous. Realizing the vision for open-ocean farming will require creativity and innovation supported by substantial investment, as well as close collaboration between nations and the business, government, and research communities.

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